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SHEAR-LAG TESTS OF A BOX BEAM WITH A HIGHLY CAMBERED COVER IN TENSION

By James P. Peterson

Langley Memorial Aeronautical Laboratory
Langley Field, Va.

NACA

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ADVANCE RESTRICTED REPORT

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SUMMARY

Bending tests were made on an open box beam designed to fail on the highly cambered tension side. Strain measurements were made to verify the applicability of previously published methods of shear-lag analysis to highly cambered sections. The average stringer stresses near the root were found to be in fair agreement with the stresses calculated by the shear-lag theory, although individual stress values showed appreciable scatter. In the strength test, the beam developed an ultimate tensile stress only a little higher than the tensile yield stress of the material.

INTRODUCTION

Deviations from the engineering theory of bending, which are commonly referred to as shear-lag effects, are most pronounced in wide, shallow box beams such as those used in many airplane wings. In wings with two shear webs, a common type of structure, the part of the cover carrying most of the load usually has relatively little camber. Advantage has been taken of this fact to simplify greatly the shear-lag theory by neglecting camber entirely and, as a result, most tests made in the past to verify shear-lag theories have been made on beams with flat covers. Inasmuch as wing covers usually do have some camber, the accuracy of the theory becomes doubtful when applied to airplane wings. Tests were therefore made in the Langley structures research laboratory of a beam having more camber than is likely to be found in an actual wing in order to determine whether the shear-lag theory (references 1 and 2) might be applied with some degree of confidence over the entire practical range of camber. Although the main purpose of the tests was to compare the experimental with the theoretical stress distribution, some data were obtained on the ultimate tensile stresses that could be developed in a built-up structure for comparison with the stresses developed in standard tensile specimens.

SYMBOLS

A cross-sectional area, square inches

P total external applied load, kips

Mz/I normal stress defined by the engineering theory of bending, ksi

σ normal stress, ksi

Subscripts:

F flange

L longitudinal stringer

ult ultimate

TEST SPECIMEN AND PROCEDURES

The test beam was constructed of 24S-T aluminum alloy with the exception of the compression flanges and the bulkheads, which were made of steel. Details of the cross section and side elevation of the beam are shown in figures 1(a) and 1(b), respectively. The beam was made symmetrical about a chordwise center line to approach as closely as possible the condition of a fixed root at that station. The camber of the cover was made large enough to insure that in spite of considerable shear-lag effect the maximum stress would occur on the spanwise center line of the beam, rather than in the corner flanges. Six stringers were attached to the cambered cover. These stringers are numbered in figure 1(a) for identification. Because of the symmetry of the cross section, the same numbers were used for stringers equidistant from the longitudinal center line of the beam. The beam was fastened to the floor by steel straps attached to the tips of each shear web. A hydraulic jack was used to apply load through a heavy yoke to the shear webs at the root of the beam.

Thicknesses of the stringers and of the sheets were determined by micrometer measurements accurate to about 0.0001 inch. Cross-sectional areas of the angles and corner flanges were determined by weighing and are believed to be accurate to better than 1 percent. The load P applied by the hydraulic jack was accurate to better than 1 percent. The strains were measured by Baldwin-Southwark SR-4 type A-1 strain gages, which were attached to the stringers and flanges near and on either side of the root station. The strain gages were always applied in pairs on opposite sides of the stringers, and strain measurements from the two opposite gages were averaged to cancel local bending effects. The strain measurements are believed to be accurate to within about 2 percent.

RESULTS

Results in the Elastic Range

The stress-strain curves of the stringer material and of the cover-sheet material are presented in figure 2. The data for these curves were obtained from standard tensile tests of three specimens of each of these materials. The results show deviations from the straight line at about 47 ksi. A few of the load-stress plots for individual stations on the box beam showed deviations at somewhat lower stresses. These deviations were possibly caused by the presence of rivet holes near the gages. At a test load of 12 kips, the highest measured stresses were about 40 ksi and were thus well within the straight-line part of all plots. This load of 12 kips, which represents about 0.69 of the ultimate load, was therefore chosen for showing stress-distribution plots representative of the elastic range.

Plots of the chordwise distribution of the stresses are given in figure 3. The stations are identified by the distance in inches from the root. In addition to the experimental data, this figure shows curves calculated by the engineering theory of bending (Mz/I) and by the shear-lag theory. The cross section of the substitute single-stringer beam used for the shear-lag calculation is shown in figure 1(c). This cross section was derived from the actual cross section by the simplest possible assumptions. The area of the substitute stringer was taken as the sum of the areas of the cover sheet and the stringers of the actual structure, and the area of the flange of the substitute structure was taken as the sum of the area of the flange and one sixth of the area of the shear web of the actual structure. The substitute half-width was taken as one-half of the actual half-width, and the depth of the substitute section was taken as the depth of the actual section measured at a point halfway between the shear web and the center line. More elaborate methods of determining a substitute cross section were tried, but they gave stresses differing only by 1 to 2 percent from those obtained by the simple method, and this difference is too small compared with the difference between calculated and experimental stresses to be of significance. The stresses in the substitute single-stringer beam were calculated by formulas (A-12) and (A-13) of reference 3. The chordwise distribution of the stresses was calculated by the method of reference 2. Inspection of the stresses at the root station shows that the chordwise distribution of the stresses is nearly uniform in spite of the large camber. The engineering theory of bending overestimates the maximum stress by a considerable margin, whereas the shear-lag theory underestimates it by a small margin. A more detailed study of the errors may be made with the aid of the spanwise plots given in figure 5.

It will be noted on the diagram in the upper left of figure 3 that the flange stresses were measured at two locations, on the inside and on the outside of the flange angles. Because of the thickness of the flange, the stresses measured by the inside gages were, strictly speaking, not directly comparable with the stresses measured on the stringers or with the calculated stresses, which are valid for points lying in the plane of the cover sheet. The error is small, but an easily applied approximate correction can be made. The inside gages on the flanges were at the same distance from the neutral axis as the intersection of the plane of the shear web and the plane of the cover. The flange stresses measured with these inside gages were therefore plotted as though the gages had been located at this intersection point, and these values were then considered comparable with the measured stringer stresses and with the calculated stresses. The stresses measured with the gages on the outside of the flanges, indicated by the diamond-shaped symbols, cannot be compared with the calculated curves because these gages are located closer to the neutral axis. A detailed study of the flange stresses is of no practical interest because these stresses are appreciably lower than the stringer stresses.

Spanwise plots of the experimental and the calculated stresses are given in figure 4. For the purpose of studying the correlation between test data and theoretical results, these spanwise plots of stresses were converted to show the ratios of calculated to experimental stresses. These ratios in figure 5 show that at individual stations, the engineering theory of bending (Mz/I) was in error by as much as 30 percent and the shear-lag theory by as much as 20 percent. Test experience with built-up sheet-metal structures tends to indicate, however, that errors at individual points are generally of much less practical significance than the average errors over certain regions. In the test discussed herein, all gage stations lay within a maximum distance of about one-fourth of the chord from the root. It is of interest, therefore, to compute the spanwise average of the errors on each stringer, and these averages are indicated in figure 5 by horizontal lines. For the flange stresses, the errors for both theories, although of opposite sign, are about the same, being 11 percent for the engineering theory of bending and 13 percent for the shear-lag theory; as noted before, however, errors in the flange stresses are of no practical interest in this beam because these stresses are too low to be critical. For the stringer stresses, the engineering theory of bending shows a maximum average error of about 20 percent (stringers 2 and 3), whereas the shear-lag theory shows a maximum average error of only 4 percent (stringer 3).

Results of Ultimate-Strength Test

The beam failed at a load of 17.5 kips. The failure was a tension failure following the line of rivets connecting the cover to the root bulkhead except for two rectangular detours about 1 inch wide to the first stringer-to-skin rivet located 1 inch away from the root. The failure did not carry over into the flanges.

Many of the strain measurements showed only very slight deviations from the straight line up to the highest loads at which readings were obtained. It was, therefore, not considered worth while to present all the load-strain data obtained, and the data showing the highest strains were selected to be presented in figure 6. The highest strain measured (stringer 1 at the root station) was 0.009 at a load of 17 kips or $0.97P_{ult}$. The stress-strain curves of the material (fig. 2) were only carried very slightly beyond the yield strain of about 0.007. They are nearly horizontal, however, at this strain, and the strain of 0.009 measured on the beam corresponds consequently to a stress only slightly in excess of the yield stress. By linear extrapolation, then, the maximum stress at failure may be estimated as slightly over 55/0.97 or about 57 ksi.

Sketchy tests made by several investigators have indicated that the failing stress in 24S-T aluminum-alloy sheet with holes is about 10 percent less than the ultimate stress developed by standard tensile specimens of the same material. The ultimate stress developed by the standard tensile specimens of the cover material was about 72 ksi (fig. 2); a reduction of 10 percent from this value yields a stress of about 65 ksi, which is considerably higher than the estimated maximum stress of 57 ksi developed by the beam. The difference appears to be too large to be explained by the scatter in the available data on stress concentration, and it is more likely that the tests made to evaluate the effect of holes on tensile strength did not contain some factor or factors existing in beam tests.

CONCLUSIONS

From the tests of an open box beam with a highly cambered cover in tension, the following conclusions were drawn:

1. The average stringer stresses near the root were in fair agreement with the stresses calculated by the shear-lag theory, although individual stress values showed appreciable scatter.

2. The ultimate tensile stress developed by the beam was only slightly higher than the tensile yield stress of the material.

Langley Memorial Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va.

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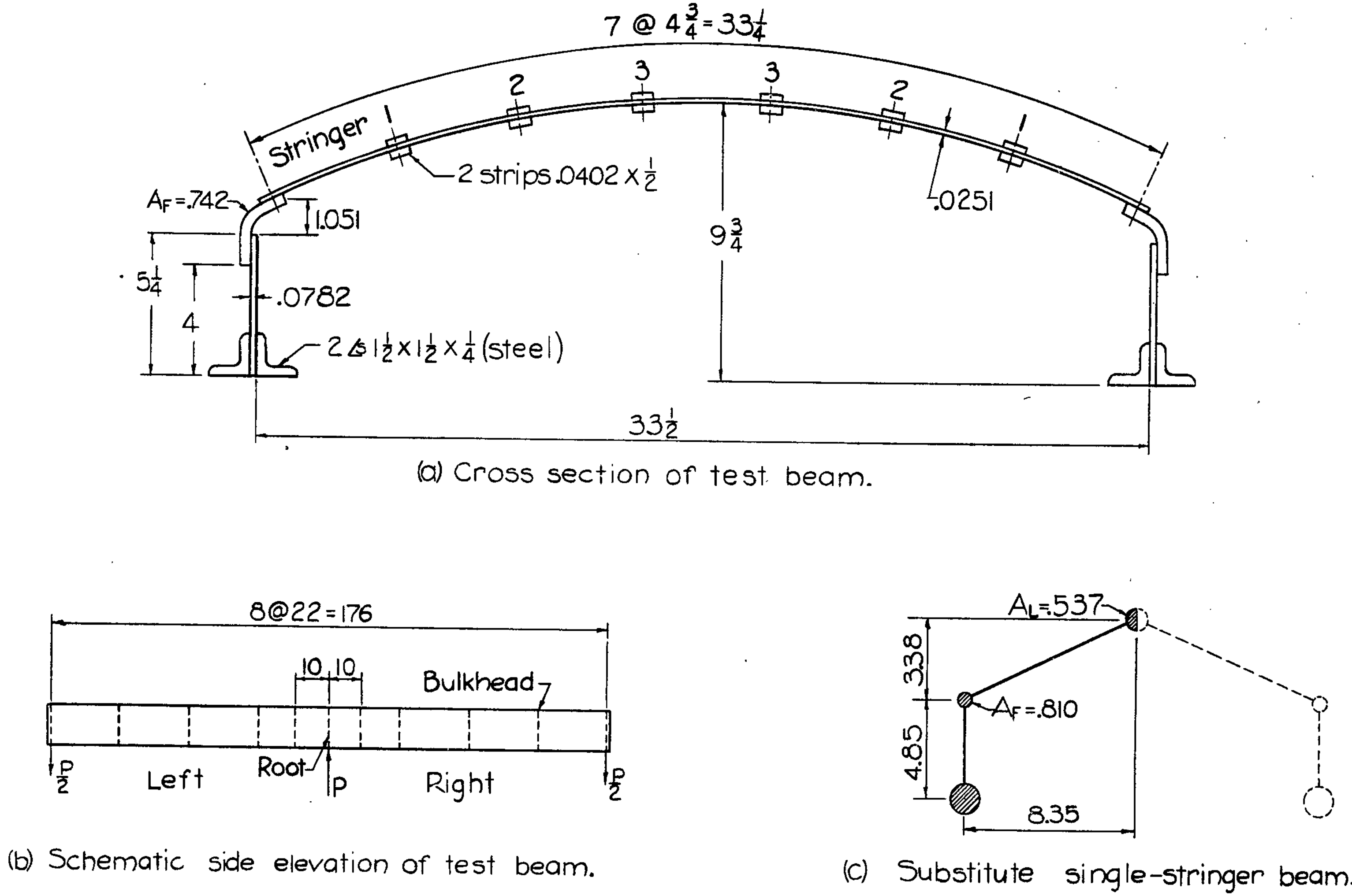

(a) Cross section of test beam.

(b) Schematic side elevation of test beam.

(c) Substitute single-stringer beam.

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Figure 1.- Details of test beam and substitute single-stringer beam.

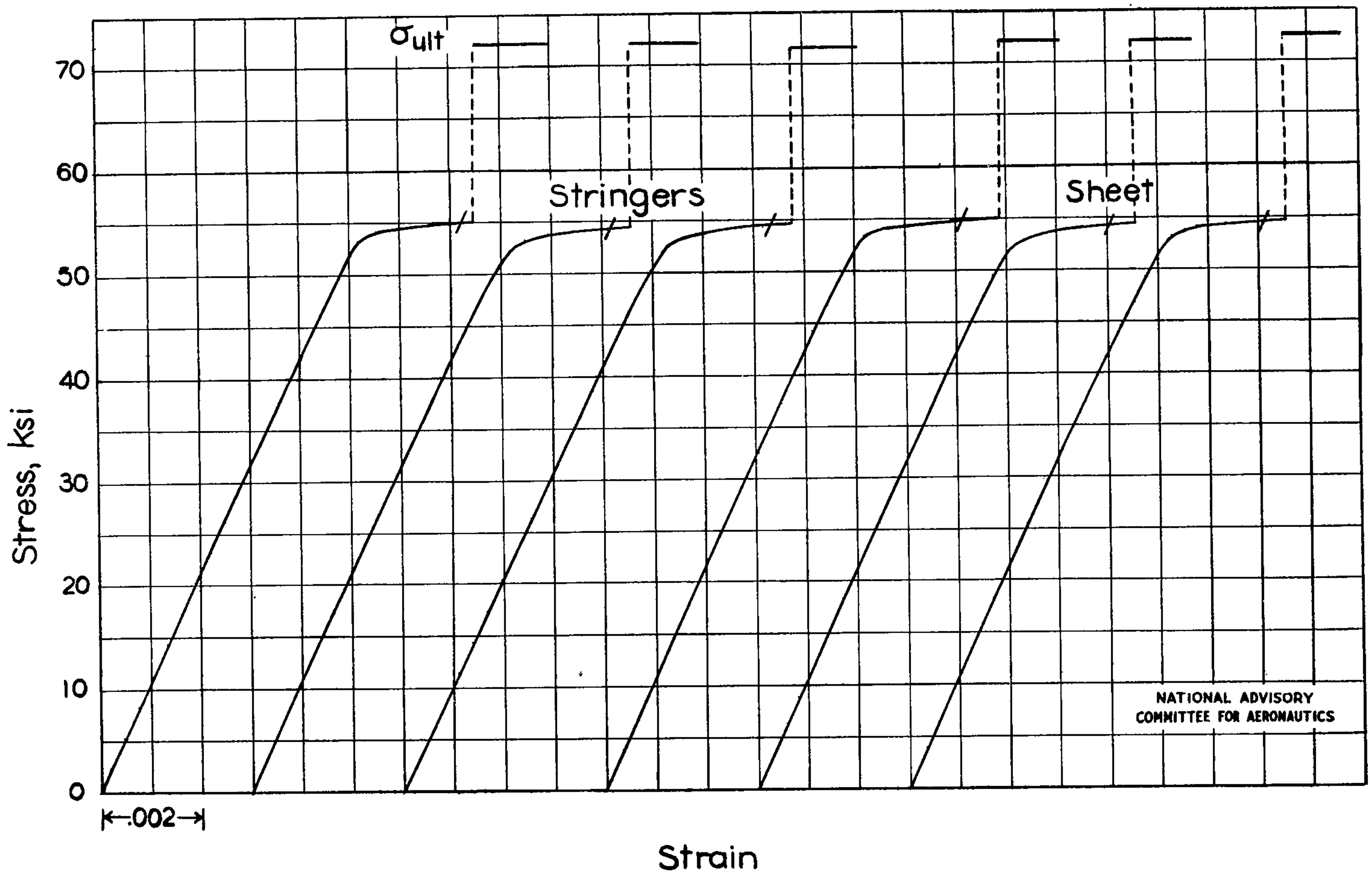

Figure 2.- Tensile stress-strain curves for stringers and cover sheet of 24S-T aluminum alloy tested in the with-grain direction.

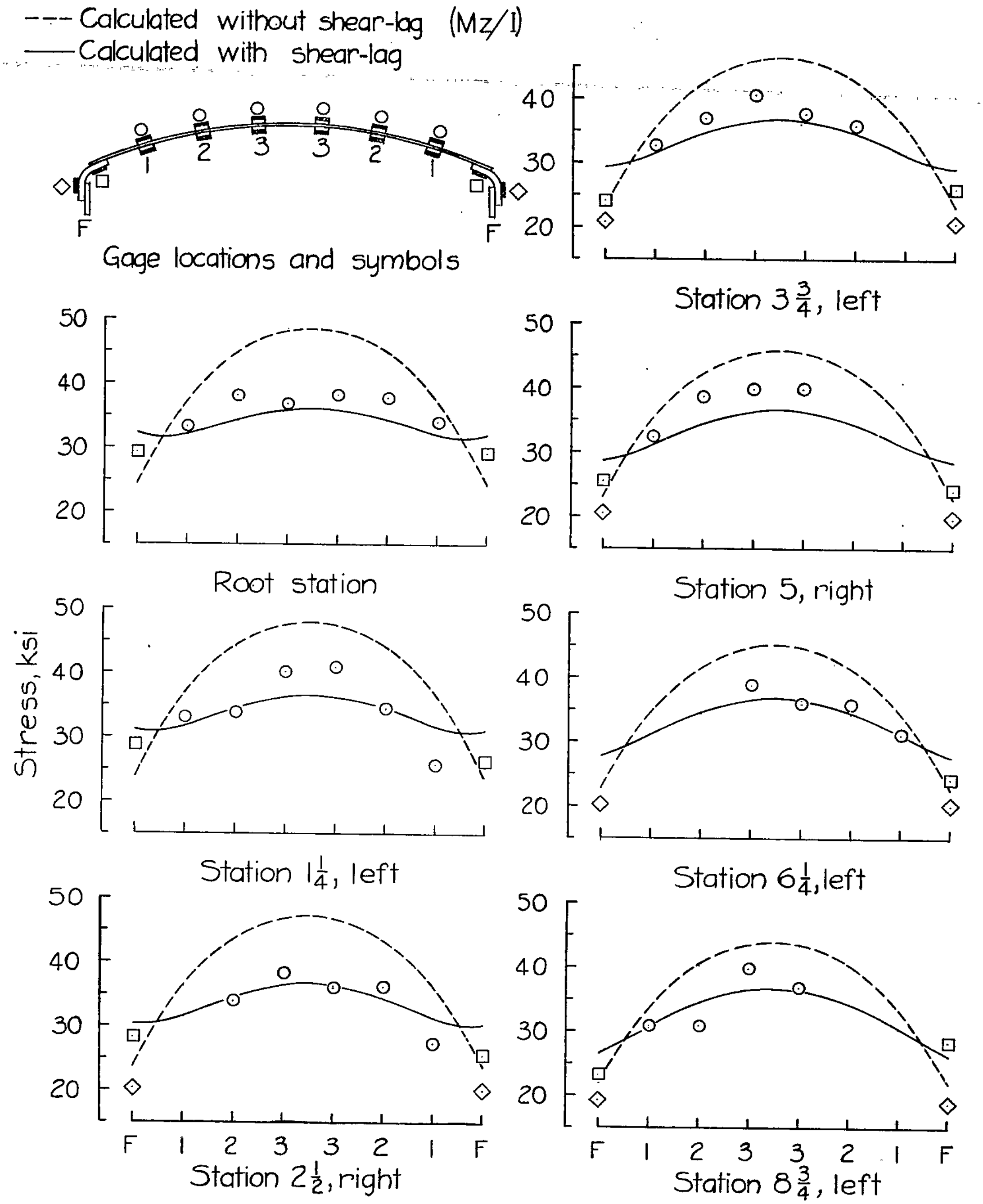

Figure 3.- Chordwise distribution of normal stresses in cover at jack load P of 12 kips. (Letter "F" indicates flange.)

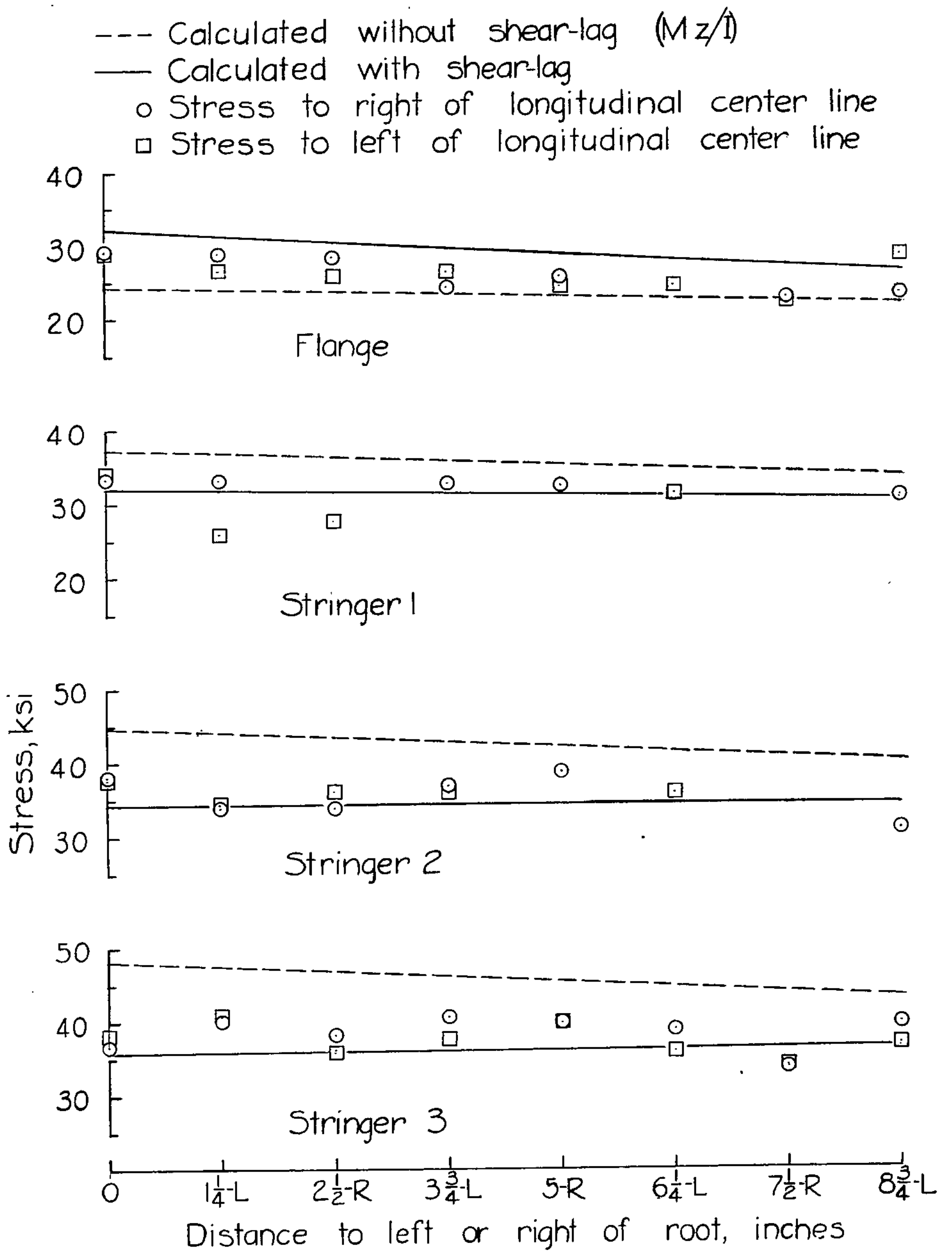

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Figure 4.- Spanwise distribution of normal stresses in cover at jack load P of 12 kips.

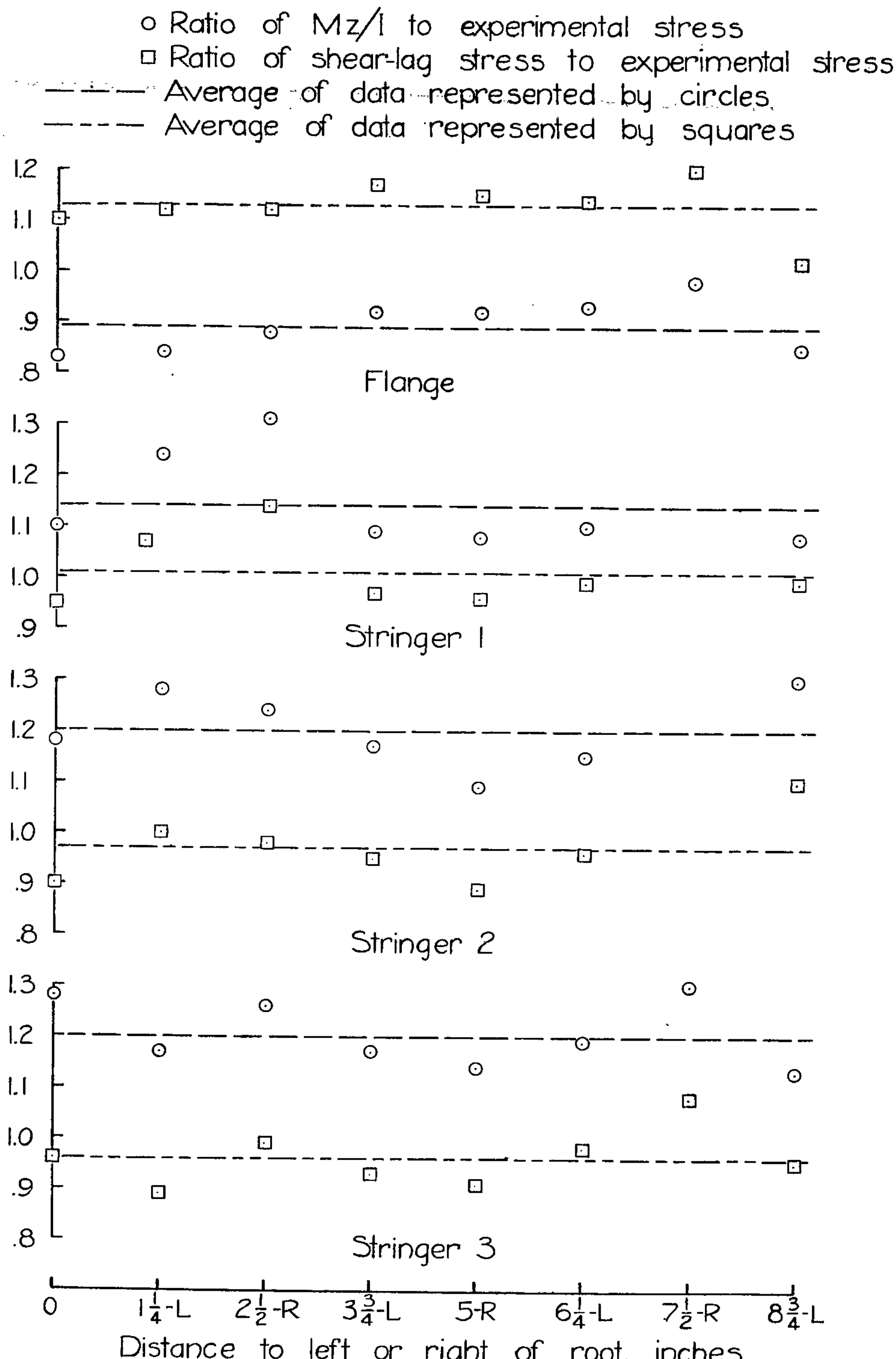

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Figure 5.- Ratios of calculated to experimental stresses in cover at jack load P of 12 kips.

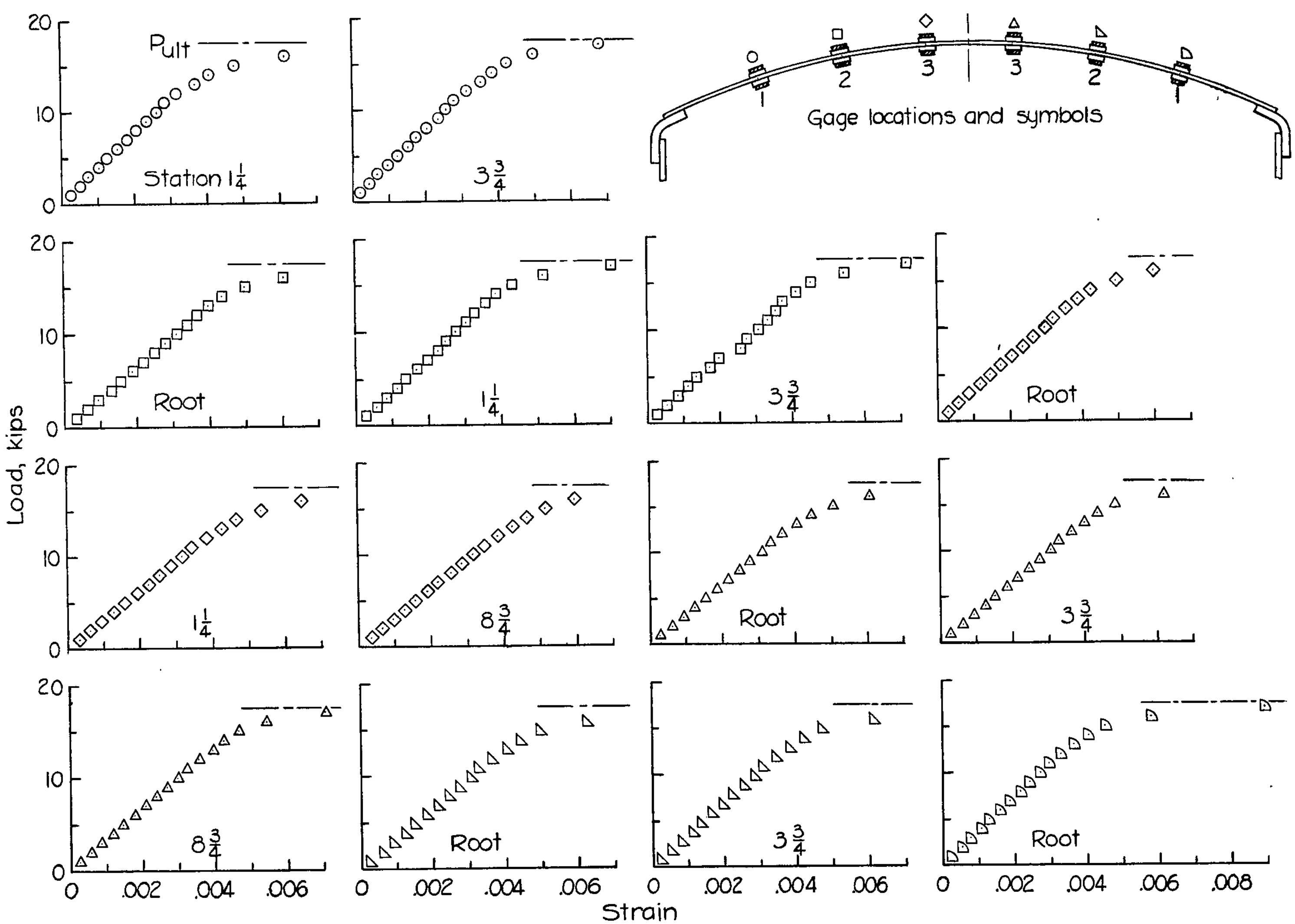

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Figure 6.- Selected load-strain curves.